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Use of Quality Control Procedures to Assess Errors in Measuring Forest Canopy Condition

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16. ABSTRACT

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USE OF QUALITY CONTROL PROCEDURES TO ASSESS ERRORS IN MEASURING FOREST CANOPY CONDITION

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Quality control data collected during the measurement of ponderosa pine canopy cover and sugar maple crown damage was analyzed. Measurement precision (root mean square of differences in replicate measurements) of pine canopy cover was high (± 2.6-4.0%) and similar for field replicates and laboratory replicates digitized with the same and different f-stops. In contrast, significant systematic errors can be introduced during certain analyses of hemispherical photographs. Measurement precision (frequency of remeasurement within ±1 class) of maple crown ratings was high (74-95%), due mainly to crew training prior to data collection. Precision was highest for branch dieback and foliage transparency and when remeasurements were done by the same crew. Using the same crews for remeasurements and emphasis of branch dieback would increase precision of data collected subsequently, but the cost of these actions should be evaluated in relation to net gain in precision and the biological importance of the response variable. The following procedures are recommended: implement training prior to data collection, use consistent methods and reference materials to control measurement errors during data collection, and include methods and quality control data with study results to provide a basis for evaluating data quality and comparability with other studies.

INTRODUCTION

Experimental results from the Forest Response Program (FRP)[1], a part of the National Acidic Precipitation Assessment Program, may be used to formulate environmental policy. Environmental policy decisions can be made with more confidence if the uncertainty associated with the experimental data is known and sufficiently low. Measurement error is one component of the total uncertainty of experimental results. One of the goals of the Quality Assurance (QA) Project of the FRP is to document measurement error associated with experimental data sets.

There are several reasons to concentrate on reducing measurement error. First, actual measurement error has not been quantified for many of the biological variables used to assess the effects of air pollution on forests. Second, measurement error can be a large portion of the total variation of an experimental data set[2]. Some measurement error is inevitable, but it may be relatively large for a difficult methodology or for one that is inappropriate or poorly executed, or when a methodology relies on instrumentation that is imprecise or inaccurate. Third, important components of measurement error are controllable through quality control (QC) procedures such as calibration, analysis of reference materials, use of defined operating

procedures, and control charting[3]. Furthermore, by setting up a proper design, the measurement errors associated with a particular method and variable can be estimated and compared, thereby facilitating the selection of the most reliable methods and variables[4]. Finally, reducing measurement error is usually cost effective because the amount of useable data increases; however, the cost of reducing measurement error should always be evaluated. In most cases it is useful to ask "How much will it cost to increase the quality of data, and is this cost justified?"

The purpose of this paper is 1) to present estimates of measurement error for some forest canopy variables, and 2) to discuss the use of QC data and procedures for reducing measurement error. Examples from the FRP will be used.

EXPERIMENTAL METHODS

Project 1

Background. The Western Conifers Research Cooperative of the FRP funded Drs. Susan L. Ustin (University of California, Davis) and Brian Curtiss (University of Colorado, Boulder) to conduct a study entitled "Remote Sensing of Forest Condition in the Western United States." A main objective of this study was to determine if oxidant-induced injury in ponderosa pine (Pinus ponderosa Dougl. ex Laws.) forests was detectable from remote sensing data.

Aircraft-based spectral data were collected on a 145 x 10 km flight line over the western slope of the southern Sierra Nevada of California, along an atmospheric pollution gradient. Ground-based data were collected in 15 stands within the flight line to provide a ground-truth and a basis for relating remote spectral data to stand and canopy characteristics. Only stands dominated by ponderosa pine were selected. Other stand selection criteria included a range of exposures to ozone, easy access, and easy location on aircraft images.

A transect of 400 m was set out through the center of each of the 15 stands, usually in two 200-m parallel lines 50 m apart. Sampling points were established every 20 m along the transect, and each of the 20 points/stand were marked with a stake. This sampling design provided a spatial average for the site over an area of several pixels (aircraft pixels = 20 m^2). Numerous types of field data were collected at each sampling point, but for the purposes of this study only the hemispherical (fisheye) photographs of the tree canopy were analyzed. Sky cover was analyzed, recognizing that percent canopy cover was 100 - % sky cover.

Measurements and QC data. A black and white photograph was taken at each sampling point by centering a camera mounted on a tripod at 25 cm above the point. The camera was aimed vertically with north at the top of the frame. The camera was leveled with the aid of a bubble level before taking the picture. A Canon AE-1 camera (tm) with a Canon fisheye lens (tm) were used to take the pictures. Exposure and f-stops were set manually and were not changed within a site. Pictures were taken under low sun angles and were completed at a site in about 1 hr.

After completing all photos the first photo point was remeasured by the same observer with the same equipment and settings. Within a site the observer was always the same, but among sites observers were different. Remeasurements were done at 8 of the 15 sites. Errors associated with field measured replicates were examined first (Type 1). Errors in this measurement may arise from inaccuracies in locating the same point for the replicate measurement, errors in leveling the camera, changes in the lighting conditions or in the f-stop at the time of measurement, and changes in the subsequent processing steps. This comparison examines the combined repeatability of all steps in the measurement process to estimate canopy cover using slides taken with the same f-stops.

Next, measurement errors from the subsequent laboratory analyses of the photos were examined. Black and white negatives were digitized using a video camera. As the camera scanned the negative, a brightness value was assigned to each pixel of a 500 x 500 grid. The brightness values depended in part upon the f-stop setting on the scanning video camera. Remeasurements were conducted to estimate the errors from use of the same f-stop (type 2) and different f-stops (type 3) during digitization.

Two other sources of error were evaluated in each of these three previous types of error. The first of these related to defining a threshold brightness to separate canopy and sky cover and the second related to weighting pixels to correct for distortion. Generally the brightness levels of the negatives appeared either white, black, or gray. The white and black areas easily separated into either sky or canopy, but the gray area could be either. Consequently, a threshold brightness was defined in order to assign the gray area to either sky or canopy. This was a subjective decision and was suspected to be the largest source of error in processing the images. In order to estimate the maximum magnitude of this error, a single interpreter set the threshold brightness at the darkest sky brightness acceptable and at the lightest sky brightness acceptable for each slide, remeasured them, and compared the difference. This produced a high and low estimate of sky cover, respectively, for each remeasured slide.

Finally, distortion was present in each hemispherical photograph because the photos were analyzed in two dimensions. Generally, the pixels in the center of the photo were over represented compared to the edge pixels. The magnitude of this error can be relatively large if the canopy is clumped rather than randomly distributed, but a standard algorithm can be applied to give the pixels equal weight, if desired. The magnitude of this error was assessed by comparing the sky cover of photos with and without the use of the weighting algorithm.

Project 2

Background. The data from this project was collected for the "The North America Sugar Maple Decline Project" and was funded by the Eastern Hardwood Research Cooperative as part of the FRP (Imants Millers, USFS NE Forest Exp. Station, Durham, NH, and Denis Lachance, Canadian Forestry Service, Ste. Foy, Quebec; Project Coordinators). The major objective of this project was to determine the rate of change in sugar maple (Acer saccharum Marsh.) canopy conditions over a wide geographic area of the US and Canada. The geographic area included the US states of Maine, Massachusetts, Michigan, New Hampshire, New York, Vermont, and Wisconsin. The Canadian Provinces include New Brunswick, Ontario. and Quebec.

During the summer of 1988, 830, 20 m^2 permanent plots were laid out across the geographic area. Groups of five plots were clustered in proximity to each other (generally orientated in a cross or in a line pattern). One-half of the total plots were located in sugarbush stands tapped for maple sugar production and the other half in undisturbed forest stands. The canopy condition of 15,642 sugar maple trees from all plots was rated during a six-week period beginning on July 15 and ending on August 31. Each sugar maple was rated for four crown characteristics: branch dieback, foliage transparency, foliage discoloration, and dwarfed foliage. To reduce individual bias, each rating was conducted by a crew of two. Each crew member rated each tree from all sides of the crown, discussed their ratings, and agreed on the final value for each of the five categories. Each crew of two used binoculars when necessary. Branch dieback, foliage transparency, foliage discoloration, and dwarfed foliage were rated in a 12-class system (Table I). The crown characteristics were defined as follows:

1) branch dieback - an estimate of the entire tree crown volume that contained branch dieback. Branch dieback was defined as the dieback that begins at the terminal end of a branch and progresses towards the main stem (as opposed to dieback that begins at the main stem and progresses outward to the branch tip).

2) foliage transparency - a volume estimate of the amount of skylight visible through foliated portion of the tree crown.

3) foliage discoloration - a volume estimate of the foliated portion of a tree crown that contained leaves some other color than green or a shade of green.

4) dwarfed foliage - a volume estimate of the foliated portion of the crown that contained leaves that were obviously (approximately 1/2 the size) smaller than other nearby sugar maples.

Remeasurements and QC Data. During the same six-week period, 843 sugar maples (5.39% of the total) were remeasured by various cooperating groups. The plots were randomly selected within a cluster of five plots and the length of time between measurements was left up to the cooperating groups. The cluster that was selected generally was the closest geographic plot between various states and provinces. The remeasurements were classified into three different types: 1) Type 1 - the trees on a plot were remeasured by the same crew as did the original rating; 2) Type 2 - the trees were remeasured by a different crew than rated the plot originally, but were personnel from the same state or province; and 3) Type 3 - same as Type 2 except the remeasurement crew was from a different state or province. Types 2 and 3 were separated because different political units required a different educational and experience background and because the error within a state or province might be smaller than from different political units. The project set an acceptable error limit of ± 1 class deviation for 90% of the observations (within a plot).

Data Analyses

The canopy cover data for project 1 was analyzed separately by type of measurement error. Graphical analysis consisted of plotting the difference between original and remeasurement in relation to the ideal target (0% difference) and of the stated precision goal of the project ($\pm 10\%$). The precision of measurements was estimated by the root mean square of the differences in replicate measurements[3]. Hypotheses regarding equality of measurement means were tested using paired t-tests[3].

The data of project 2 consisted of tree crown and injury variables measured as discrete class ratings. The reported class deviations were based on the original rating. Since the different remeasurement types were focused on different stands at varying points in time, analysis of the variability in remeasurement is limited to comparisons of frequencies and similar graphical comparisons as used in project 1.

RESULTS

Project 1

Similar precision estimates (± 2.6-4.0%) were calculated for field replicates (type 1), and lab replicates digitized using either the same (type 2) or different f-stops (type 3) (Table II). Individual remeasurements usually differed < ±5% from originals for each type of error analyzed (Figure 1). Individual values of photos digitized with different f-stops showed a greater degree of variability and since the difference was calculated as original minus remeasurement, the plot indicates that the remeasurements were consistently lower than the originals. The original and remeasurement means were found to be significantly different (paired t-test, P=0.01).

A measurement error of more significance than precision was the selection of a threshold brightness value, which controlled the high and low sky cover estimates. This analysis showed that for both the unweighted and weighted estimates the high and low means were significantly different for each type of error analyzed (paired t-test, P=0.01) (Table II). Mean high sky cover estimates were 10-13% greater than low estimates. These results must be considered in their proper context, mainly that they represented a contrived "worst-case" example of the effects of using very different threshold values between remeasurements. In reality all photos in project 1 were analyzed by one interpreter, and it is unlikely that this interpreter would introduce a large systematic difference between photo remeasurements. The implications, however, remain important: the interpreter's decision about the threshold value is the crucial step in repeatability of the fisheye cover measurements and when more than one interpreter is working on the same set of photos, they must use consistent techniques to avoid introducing systematic errors. Systematic error is also possible if personnel change year to year, as is likely in long-term monitoring projects. Such errors can be controlled by using one or more reference photos to calibrate between observers, measurement sessions, and years. A plot of repeat measurements of these reference photos on a control chart can be used to track performance and make necessary adjustments (instrument calibration, retraining) if drift becomes a problem.

Finally, weighting pixel values must be recognized as a potentially significant source of error during processing of hemispherical photographs. This analysis showed that for both high and low sky cover estimates the unweighted and weighted means differed significantly for each of the three types of errors analyzed (Table II). Mean unweighted estimates were 4-5% greater than mean weighted estimates. This systematic error

would be of less consequence if the weighting procedure, if any, was applied consistently to all the photos in a study, and if the data were reported as unweighted or weighted so that their comparability with data from other studies could be evaluated.

Project 2

As expected, the same-crew remeasurements (Type 1) generally had the highest precision. Errors were similar for branch dieback, foliage transparency, foliage discoloration, and dwarfed foliage (Table III). This precision met the stated precision goal of the project of 90% of the remeasurements ±1 class from the original. The implication of this precision level is that if monitoring showed a ±2 class change in a crown or injury class, there would be high assurance that measurement error was not the cause.

Precision decreased for all crown and injury ratings, except dwarfed foliage, when different crews made remeasurements. Different crews from the same state/province (type 2) produced data of a precision similar to, but generally slightly lower than, that of same crew remeasurements. As expected, remeasurements based on crews from different states/provinces (type 3) had the lowest precision. For example, the stated precision goal of ±1 class was met as follows: dwarfed foliage (74%), foliage transparency (78%), foliage discoloration (81%), and branch dieback (95%). For these variables (except branch dieback) a ±1 class change detected by monitoring with crews from different states/provinces has a moderately high chance of being masked by measurement error; here the assurance of little influence from remeasurement error does not occur until ±2 classes.

Graphical comparisons confirmed that dieback was easier to remeasure than transparency when remeasurements were made by different crews (Figure 2). For both dieback and transparency there was much less spread for measurement type 1 about the ideal remeasurement difference of 0 than for measurement types 2 and 3.

A small positive correlation between remeasurement error and elapsed time between measurements of foliage transparency was found for remeasurement type 2 ($r=0.17$, $P=0.001$). Elapsed times for remeasurement types 2 and 3 were longer than for type 1, thus providing opportunity for larger changes in canopy condition and in observer preceptions or expertise. This error may be mimimized by making remeasurements on the same day or requiring the same elapsed time between measurements, or by recording elapsed time between measurements so that the effects of different elapsed times can be examined and adjusted, if needed.

The remeasurement data can serve several important uses. First,

they quantify the lower limits for detection of change. In this study any change $\leq \pm 1$ class probably can not be detected because of measurement error. Second, it provided some indication of the reliability of measurements of different forest canopy variables. For example, in this remeasurement program branch dieback and foliage transparency were more easily reproduced by all crews, and thus are more reliable for detecting trends. However, the four tree canopy condition variables had similar measurement precisions when different crews from different states/provinces were not used.

Finally, the remeasurement data provided information for increasing the precision of data collected in the future. For example, the relative increase in quality of data (i.e. higher precision) by the use of the same crew for all measurements would have a cost--mainly the money needed to travel from site to site. This cost would be considerable in a project such as this, where a large geographical area has been covered. This cost, coupled with the knowledge that little quality was lost by using different crews from the same state/province, would probably not be justified because it does not increase quality substantially. In addition, if different crews from different states/provinces will be used in future monitoring, data collection may want to concentrate more upon branch dieback and foliage transparency because they can be measured with more precision. Another option would be to attempt to reduce measurement errors of variables that prove difficult to measure, e.g., by refining definitions and increasing training. Again though the cost of these activities must be evaluated. If the variables in question are biologically critical or sensitive, then the extra cost may be justified.

These uses of the QC data are most beneficial when used early in this type of a project. For example a pilot study should include a test of the QA program as well as that of the experimental design and sampling procedures. An important part of a test of the QA program would be training sessions. Training sessions have several benefits: 1) introducing the personnel to the methodology, 2) early collection of data on remeasurement error, 3) identifying ambiguities in the methodology and how they contribute to measurement error, and 4) the opportunity to revise methods so that errors are reduced before data collection starts. For example, this project used such information from a training session to alter the procedure for rating individual trees; a second individual was added to each crew. Then both individuals rated the tree separately, by viewing all sides. Acceptable ratings had to be $\leq \pm 1$ class. This rating was more reliable than individual ratings because it more truly represented the whole crown and tended to average out observer bias.

Doing these types of exercises in a pilot or training setting solidifies the connection between the experimentally important variables, the magnitude and sources of errors associated with the collection and measurement of those variables, and the types of QA activities and QC data needed to monitor, reduce, and document those errors. Conducting these types of exercises prior to data collection increases the amount of potentially usable data, the quality of which is documented concurrently.

CONCLUSIONS

Several key results can be identified from this analysis of measurement error in assessment of forest canopy condition:

1) Measurement precision (as the root mean square of the differences in replicate measurements) of ponderosa pine canopy cover was quite high ($\pm$ 2.6-4.0%) and similar for field and laboratory replicates measured with the same and different f-stops. In contrast, systematic error introduced during certain laboratory analyses of photos was found to be potentially significant, but controllable by use of a consistent methodology on all photos and continuous monitoring with "in-house" reference photos.

2) Measurement precision (as frequency of remeasurement $\leq \pm 1$ class) of sugar maple crown damage ranged from 74-95% for remeasurements made by crews from different states/provinces. Measurement precision was lowest when the remeasurement crews were from different states/provinces and highest when remeasurements were done by the same crew. High quality data were attained mainly due to training of field crews prior to data collection. The easiest variables to remeasure were branch dieback and foliage transparency. Use of the same crews for remeasurements and emphasis of these variables in future data collection sessions would improve data quality (i.e. higher precision), but the cost of these actions would have to be evaluated in relation to the relative gain in precision and the biological signficance of the measurement variable.

These results have immediate usefulness to the two projects analyzed. In this sense the results are project specific and their generality remains in question. The QA Project of FRP is continuing to analyze and summarize QC data from other FRP projects for a variety of variables. At the end of this process more definitive estimates of measurement error of canopy condition and other variables can be stated.

Even though the data presented here were specific for these projects, the information on the use of QC data can be used in a

generalized manner. Also, the data for forest canopy condition that was presented can be used by other projects as a guideline until actual project data is available. Finally, the following general procedures are recommended: 1) implement training prior to data collection in order to increase the amount of potentially usable data, 2) use consistent methods and reference materials to control measurement errors during data collection, and 3) include detailed methods and QC data with study results to provide a basis for evaluating data quality and comparability with other studies.

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Table I. Class percentage, and range for estimates of sugar maple branch dieback, foliage transparency, foliage discoloration, and dwarfed foliage for project 2.

Class Percentage	Class Percentage Range
0	0
5	1 - 5
10	6 - 15
20	16 - 25
30	26 - 35
40	36 - 45
50	46 - 55
60	56 - 65
70	66 - 75
80	76 - 85
90	86 - 95
100	96 -100

Table II. Measurement errors in using hemispherical photography to estimate ponderosa pine canopy cover for project 1. Data are % sky cover=100 - % canopy cover.

Remeasurement Type	Mean	Sm[a]	Sm[a] Relative	Sd[b]	Sd[b] Relative	N[c]
Field Replicates (Type 1)						
high sky cover unweighted	59.6[d,e]	11.3	19.0	2.6	4.4	16
low sky cover unweighted	46.6	14.1	30.4	3.1	6.7	16
high sky cover weighted	55.5	11.1	20.0	2.6	4.7	16
low sky cover weighted	42.4	13.5	31.9	3.3	7.8	16
Digitize same f-stop (Type 2)						
high sky cover unweighted	63.2	15.3	24.1	2.9	2.6	20
low sky cover unweighted	53.0	16.8	31.8	3.5	6.6	20
high sky cover weighted	58.9	15.2	25.7	3.1	5.3	20
low sky cover weighted	48.6	16.2	33.3	3.4	7.0	20
Digitize different f-stop (Type 3)						
high sky cover unweighted	65.7	11.0	16.7	3.2	4.9	36
low sky cover weighted	53.8	14.4	26.7	3.6	6.7	36
high sky cover weighted	60.9	11.0	18.1	3.7	6.1	36
low sky cover unweighted	48.7	13.9	28.5	4.0	8.2	36

[a]Sm=standard deviation of all measurements. Sm Relative=Sm/mean X 100.

[b]Sd=root mean square of differences in replicate measurements. Sd Relative=Sd/mean X 100.

[c]Total number of measurements.

[d]For each remeasurement type, means of high and low sky cover estimates were compared (paired t- test). Unweighted means and weighted means were compared separately. For each comparison in each data set, these means were significantly different (P=0.01).

[e]For each remeasurement type, means of unweighted and weighted sky cover were compared (paired t-test). High and low means were compared separately. For each comparison in each remeasurement type, these means were significantly different (P=0.01).

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Table III. Percent of remeasurement values 0, ±1, and ±2 classes from original value for sugar maple branch dieback, foliage transparency, foliage discoloration, and dwarfed foliage for project 2.

Remeasurement Type[a]	Branch Dieback			Foliage Transparency			
	0	±1	±2	0	±1	±2	N[b]
1	66.2	94.5	94.5	67.6	95.2	97.9	145
2	59.3	93.2	98.2	45.7	91.4	97.7	396
3	57.3	95.4	98.7	34.4	78.8	96.4	302

Remeasurement Type[a]	Foliage Discoloration			Dwarfed Foliage			
	0	±1	±2	0	±1	±2	N[b]
1	71.7	96.6	100.0	67.6	88.3	93.1	145
2	62.9	96.0	98.7	81.8	96.5	98.0	396
3	48.7	80.5	81.5	56.0	73.5	82.1	302

[a] 1=same crew, 2=different crew, same state/province, 3=different crew, different state/province.

[b] Number of trees remeasured.

NOTE TO EDITORS

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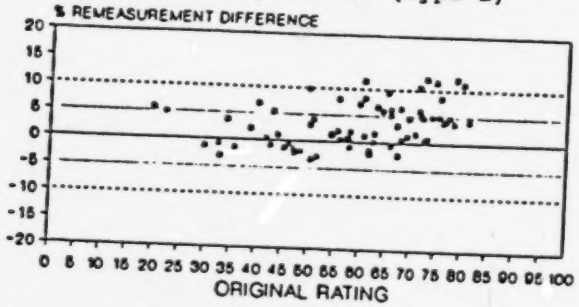
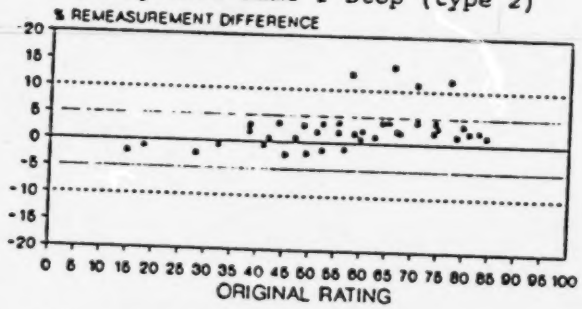
Figure 1. Percent (%) remeasurement difference for replicate measurements of ponderosa pine canopy cover by remeasurement type for project 1: a.) field replicates (type 1), b.) digitize same f-stop (type 2), and c.) digitize different f-stop (type 3). % remeasurement difference = [original % sky cover - (remeasurement % sky cover/original % sky cover)] x 100. Frequencies: x = <6, + = 6-10, and * = >10.

a.) field replicates (type 1)



b.) digitize same f-stop (type 2)



c.) digitize different f-stop (type 3)

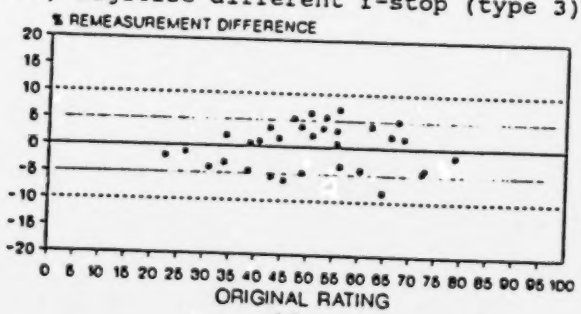
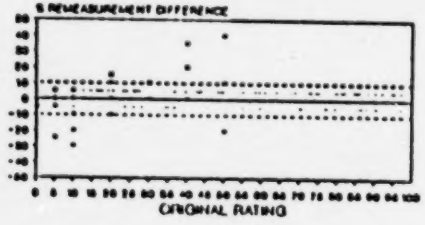
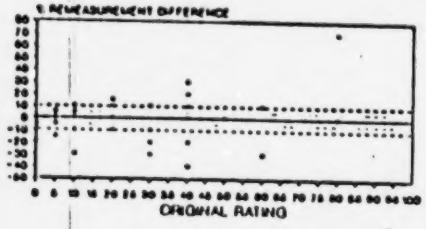


Figure 2. Percent (%) remeasurement difference for replicate measurements of sugar maple branch dieback (a, b, c) and foliage transparency (d, e, f) by remeasurement type for project 2: same crew (type 1); different crew, same state/province (type 2); and different crew, different state/province. (type 3). % remeasurement difference = original class rating - [(remeasurement class rating/original class rating)] x 100. Frequencies: x = <6, + = 6-10, and * = >10.

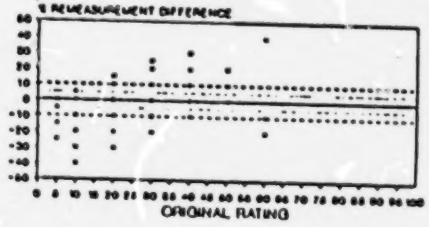
a.) branch dieback (type 1)



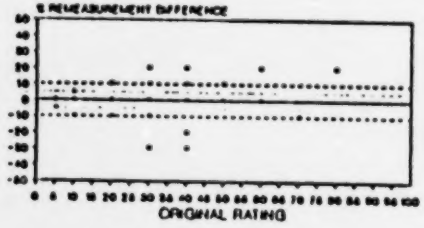
b.) branch dieback (type 2)



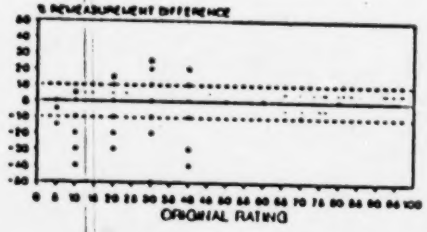
c.) branch dieback (type 3)



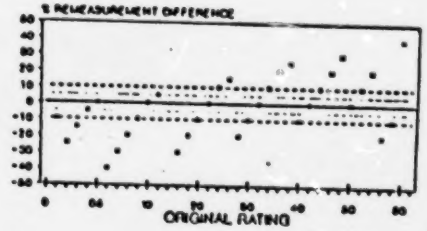
e.) foliage transparency (type 1)



d.) foliage transparency (type 2)



f.) foliage transparency (type 3)



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